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14. ABSTRACT
All insect wings possess some degree of anisotropic compliance. Typically this is evident as a pronounced bending compliance along the chord-wise direction relative to the span-wise direction. The function of this feature is unknown; does this compliance arise as a biomaterial limitation or is this indicative of advantages in terms of propulsive efficiency or maneuverability? This proposal aims to answer this question while simultaneously developing design rules for the airfoils of high performance flapping-wing micro air vehicles. To date, numerical studies of flapping wings have been hindered by the overwhelming computational expense of solving the Navier-Stokes equations for an oscillating system with distributed compliance. Instead, we will pursue a highly empirical approach which leverages the facilities and expertise of the Harvard Microrobotics Lab. In previous research we have established the capability to create artificial insect wings with well defined mechanical properties. We have also created design and fabrication paradigms which enable the construction of wing drive mechanisms at the scale and wing-beat frequency of insects. We use these techniques to perform at-scale experiments on a variety of wings chosen to span appropriate parameter spaces in the overall airfoil design. This has focused on the aeroelastic ‘passive rotation’ dynamics and planform geometry. This is the first such study in which we make no scaling assumptions on the aerodynamics.

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PI: Robert Wood
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All insect wings possess some degree of anisotropic compliance. Typically this is evident as a pronounced bending compliance along the chord-wise direction relative to the span-wise direction. The function of this feature is unknown; does this compliance arise as a biomaterial limitation or is this indicative of advantages in terms of propulsive efficiency or maneuverability? This proposal aims to answer this question while simultaneously developing design rules for the airfoils of high performance flapping-wing micro air vehicles. To date, numerical studies of flapping wings have been hindered by the overwhelming computational expense of solving the Navier-Stokes equations for an oscillating system with distributed compliance. Instead, we will pursue a highly empirical approach which leverages the facilities and expertise of the Harvard Microrobotics Lab. In previous research we have established the capability to create artificial insect wings with well defined mechanical properties. We have also created design and fabrication paradigms which enable the construction of wing drive mechanisms at the scale and wing-beat frequency of insects. We use these techniques to perform at-scale experiments on a variety of wings chosen to span appropriate parameter spaces in the overall airfoil design. This has focused on the aeroelastic 'passive rotation' dynamics and planform geometry. This is the first such study in which we make no scaling assumptions on the aerodynamics.

Final Report

1. Motivation

Insect wings deform appreciably during flight. Does this compliance have some functional significance? Or is this simply a consequence of biomaterial limitations? This thought allows us to pose a challenge for understanding flapping-wing flight: what is the role of aeroelastic compliance in flight performance? More specifically, since we are ultimately interested in applying these answers to MAVs: how is thrust production affected by the material and geometric properties of a flapping wing? To answer this question, there are multiple methods available to study the functional morphology of flapping wings. Computational fluid dynamics (CFD) is a numerical approach to solving the Navier-Stokes equations. For flapping-wing MAVs/animals in general, accurate CFD becomes computationally very expensive. When the airfoils are deformable, this requires coupling between the fluid and the deformable structure and quickly becomes challenging to the point of being intractable. As an alternative, researchers have utilized an experimental approach using dynamically-scaled models of flapping wings [1]. This involves larger, slower-moving (and thus easier to instrument) wings flapping in a viscous fluid in such a way that the Reynolds number is conserved (relative to the insect in question). However, all such models assume rigid plates and thus aeroelastic compliance is difficult, or impossible if considering inertial effects simultaneously. Finally, direct biological studies are possible, but limiting in terms of the available morphological diversity.

An alternative method, unique to the Harvard Microrobotics Lab, is at-scale measurements with biomimetic insect wings. Given the ability to manufacture insect-like wings and drive at insect-like trajectories and operating frequencies, we can perform at-scale measurements which are fast and carry no scaling assumptions. However, this requires *significant* infrastructure for force sensing, motion reconstruction, and flow visualization and thus a large portion of this project involved the realization of these components. Using the resulting system, we have performed a number of studies on various geometrical and compliance properties of flapping wings.

2. Background

In 2007, Wood demonstrated the first at-scale robotic insect (shown in Fig. 1) capable of generating thrust greater than its body mass and achieving liftoff [2]. This proved the feasibility of flapping-wing robotic insects, but left many open questions. For example, the robot in that demonstration was tethered for power, leaving the door open for studies of small-scale power storage and distribution. The robot was constrained to only move vertically, thus motivating studies in control for computation-limited systems. Most relevant to this project, the airfoils were simple adaptations of some of the gross morphological features present in flies (i.e. similar aspect ratio and area distribution). But these airfoils were in no way optimized, in terms of geometry or compliance, to maximize thrust production. This is the motivation for the studies described here.

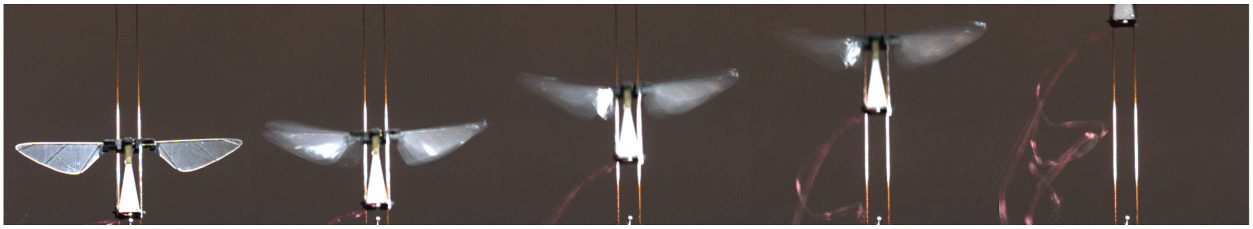

Fig. 1: First generation of the Harvard Microrobotic Fly: the first robotic insect to generate thrust greater than body weight.

3. Definitions

To make these questions tractable and allow us to design our experiments appropriately, it is important to define what we mean by 'aeroelasticity' with respect to the wings of our robotic insect MAVs. As discussed below, the basis of our flapping wing MAVs (and there is evidence that this is also somewhat present in many insect species) is passive wing rotation. This means that the wing is flapped actively using a power actuator (piezoelectric in this case) and there is a passive wing hinge that allows the wing to rotate along an axis approximately parallel to the leading edge. This rotation defines the angle of attack and is determined by the combination of inertial and aerodynamic forces acting on the wing and the stiffness of the wing hinge. Our experimental approach is therefore targeted to the first rigid body rotation mode of wing deformation, however, the methods that we have developed are extendable to higher order compliant modes (e.g. wing bending).

4. Experimental approach

Our experimental approach covered three areas: (1) development of the experimental infrastructure, (2) quasi-steady modeling of aeroelastic compliance, and (3) studies of relevant wing geometric parameters. The experimental infrastructure includes a process to manufacture insect-like airfoils with fiduciary markets to enable high precision tracking, a drive mechanism for creating insect-inspired trajectories, a high resolution multi-axis force sensor, and a vacuum chamber to house the experiments. This system is described in more detail later. Using components of this system, our first set of experiments validated that a quasi-steady blade-element model can capture the dynamics of the first aeroelastic mode of the wing motion: passive rotation. Finally, we used the system to study the effect of various shape parameters on aerodynamic performance.

An overview of the experimental infrastructure developed for this work is shown in Fig. 2. Each of the components required substantial development. The piezoelectric actuator and wing drive mechanism utilized similar technologies as in [2]. By the nature of the high bandwidth piezoelectric actuators, we are able to produce wing motions at frequencies relevant to insect flight (typically in the 50-200Hz range). With flapping commanded by the power actuator, optimal thrust is achieved by wing geometry and compliance - both leading to trajectories that create positive angles of attack on the upstroke and downstroke (similar to flies and bees in hover). A prototype wing and wing hinge are shown in Fig. 2. Note the fiducial markers present on the surface of the wing which are necessary for our method of visual motion tracking. The geometry of the flexure hinge is variable (with relevant parameters shown in Fig. 2) to allow us to tune the hinge stiffness.

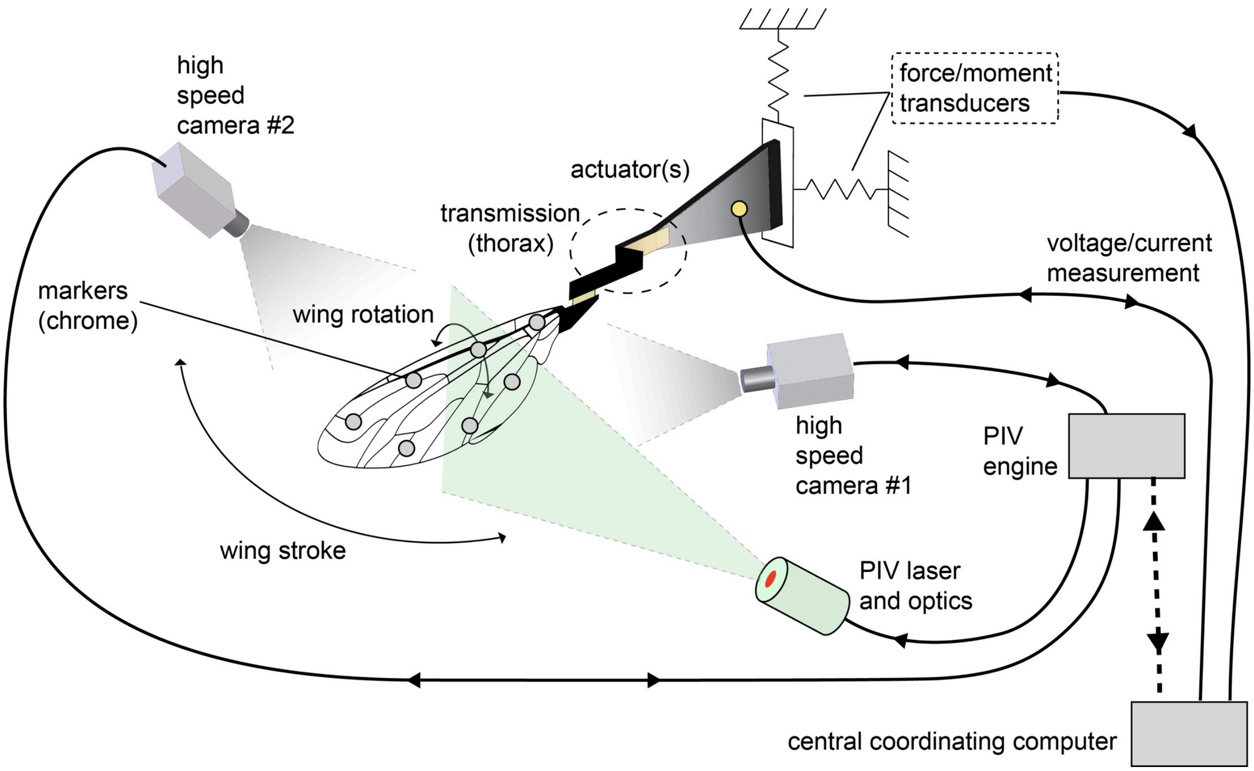

Fig. 2: Diagram of the complete test setup. A single wing is driven with a piezoelectric actuator coupled to the wing using a flexure-based transmission. The wing-transmission-actuator components are created using our custom meso/micro fabrication methods. This is capable of a wide range of operating frequencies (up to approximately 150-200Hz, depending on the wing inertia) at wing stroke amplitudes up to approximately 120 degrees peak-to-peak. Multiple high speed video cameras are use for motion reconstruction (at 10,000fps) and flow visualization. The wing drive mechanism is fixed to custom multi-axis force sensors which measure lift and drag with approximately 1kHz bandwidth and 1% body mass (hypothetical) resolution. We also measure current and voltage to the actuator to calculate the input electrical power. Optics for illumination (both for high speed video and forming laser sheets for flow visualization) are a critical component.

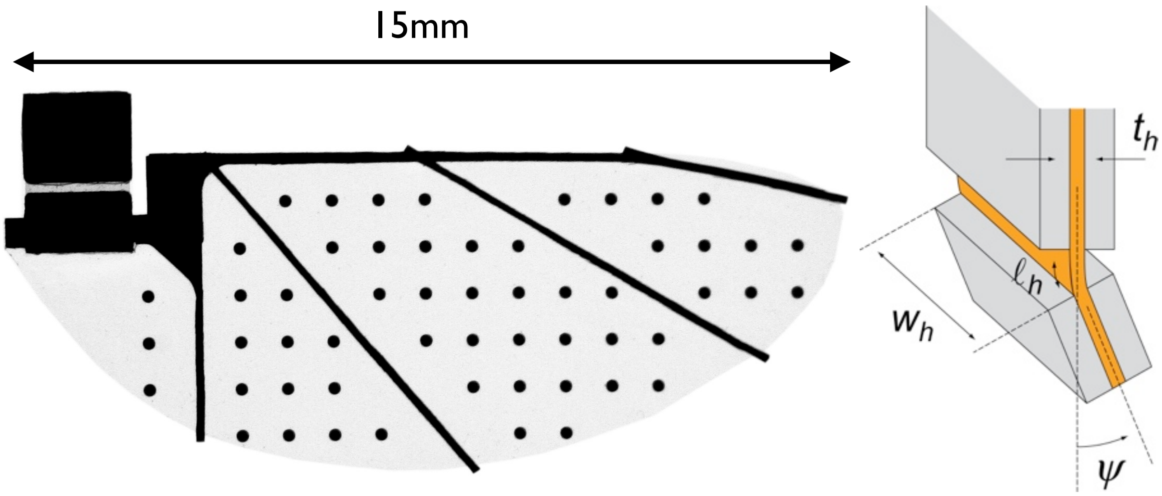

Fig. 3: Diagram of typical artificial insect wing planform (left) and wing hinge (right).

The complete wing drive mechanism, with wing, flexure-based transmission mechanism, and piezoelectric actuator is shown in Fig. 4. The drive mechanism is mounted to a carbon fiber truss structure that is designed to mount flush to a custom force sensor. The force sensor [3] is a compound cantilever beam that produces two decoupled displacements that are correlated to orthogonal forces acting on the input plate (where the wing drive is mounted). This corresponds, after a rotation for drag, into lift and drag forces produced by the wing. Capacitive displacement sensors read the displacement and convert to an analog voltage that is calibrated to lift and drag forces and read by a data acquisition system. The sensor is designed to have a force sensitivity on the order of a few milligrams and a bandwidth of approximately 1kHz. This complete system is shown in Fig. 5.

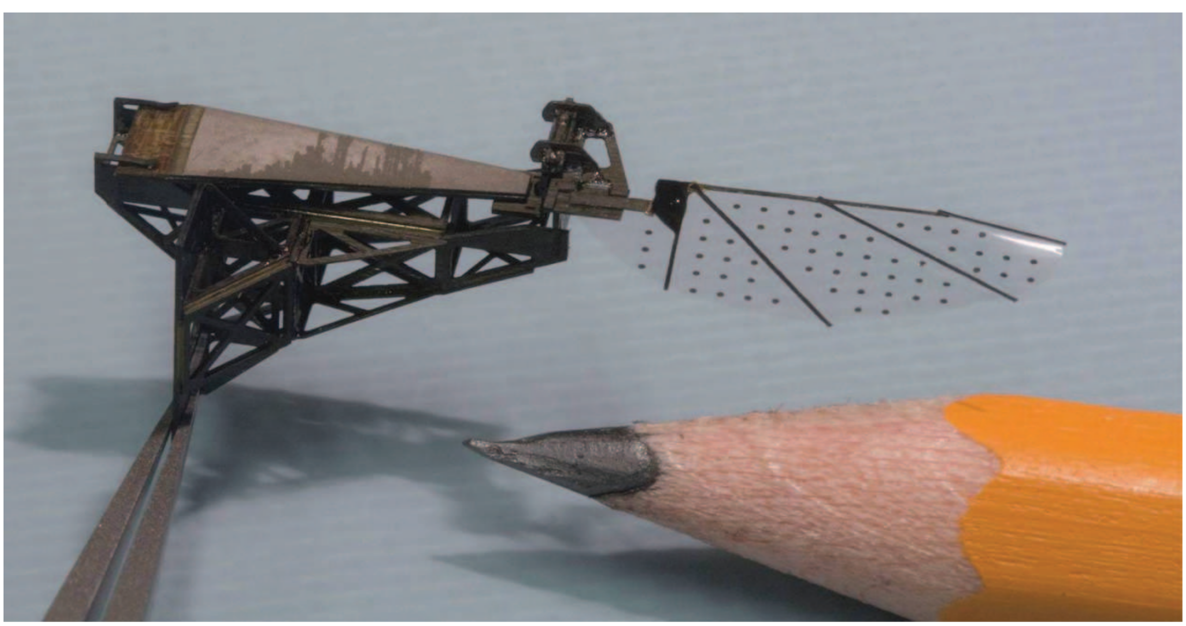

Fig. 4: Detail of the wing drive mechanism with piezoelectric actuator (gray trapezoid), flexure-based transmission, and wing.

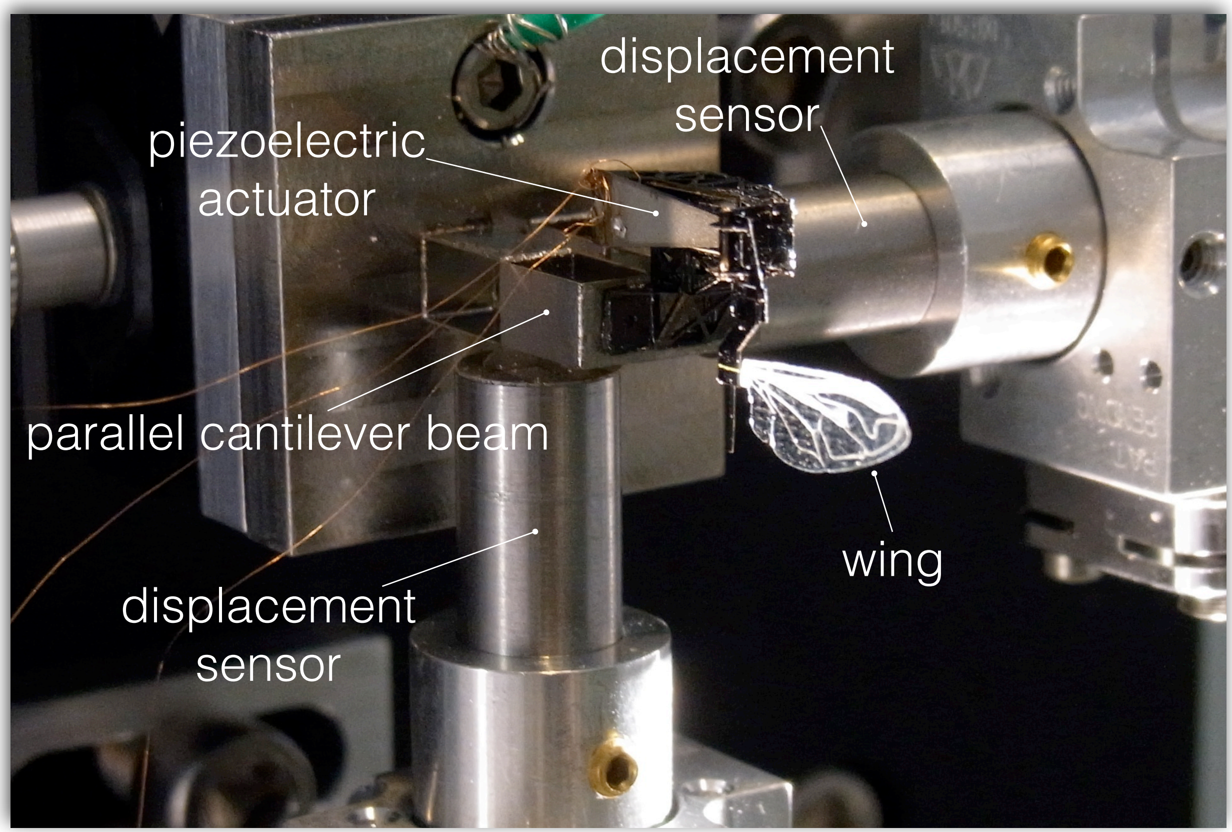

Fig. 5: Detail of the wing drive and sensing mechanisms.

The system shown in Fig. 5 is enclosed in a chamber that allows us to perform inertial tares and inject controlled seed particles for flow visualization. As depicted in Fig. 2, multiple high speed cameras are used to extract the motion (and deformation) of the wing. An example of the motions seen from the cameras at 10,000 frames per second for a wing flapping at 100Hz is shown in Fig. 6.

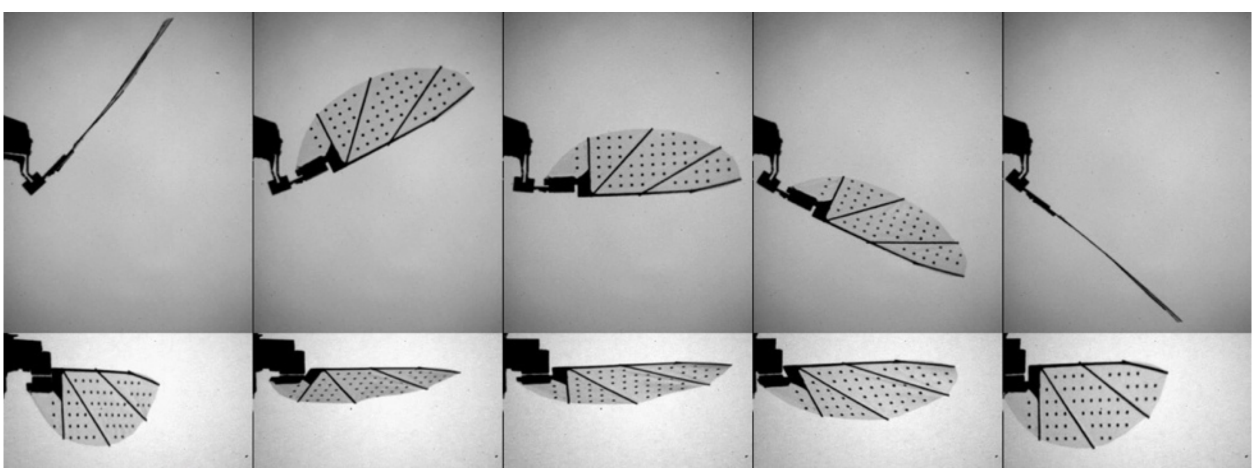

Fig. 6: Typical wing motion during one half cycle for top (top) and lateral (bottom) perspectives.

Using part of the above described experimental tools, our fist experiments validated the use of a quasi-steady blade-element method for predicting the forces acting on a wing undergoing passive rotation. We developed a model [4] that includes the inertial forces along both wing rotational axes, elastic forces from deformation of the flexure hinge, and aerodynamic forces estimated from a blade element model with force coefficients derived from Dickinson [1]. We showed that, with appropriate force coefficients, the blade element method adequately predicts not only the forces acting on the wings, but also the passive deformation (passive rotation) of the wing. This is shown for the 'baseline' case of 100Hz flapping in Fig. 7. Note that in Fig. 7, ϕ represents the flapping angle, θ is the stroke plane deviation angle (in general, this is ignored in these studies), and ψ is the rotation angle. Not only does the blade element method capture the average values for forces, the sub-period features of the forces and motions are also accurately predicted.

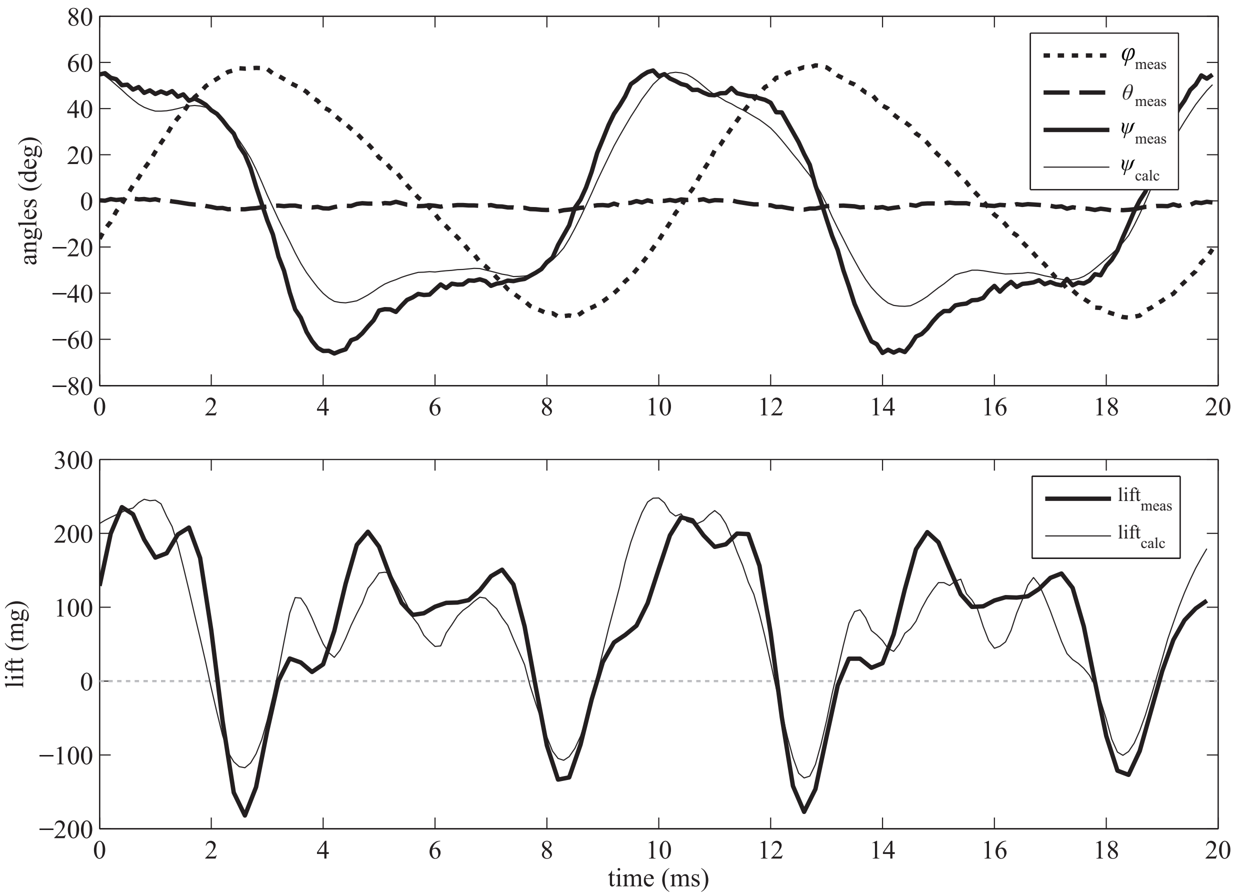

Fig. 7: Results from the baseline flapping experiment at 100Hz. The upper panel shows the three wing angles and the bottom panel the measured and predicted lift force.

In addition to this baseline case, we have also run experiments at a lower frequency (70Hz) - with hinge compliance tuned to achieve adequate rotation - and a 'split-cycle' trajectory where the wing velocity is increased in the upstroke and decreased in the downstroke. In both of these cases, the model again accurately predicts the motions of the wing and the forces acting on the wing. These experiments and results are described in more detail in [4]. This remarkable accuracy validates the use of a quasi-steady modeling method for this case. It should be noted that this does not validate the model for all conditions (e.g. for different wing geometries or Reynolds numbers). However, it gives us a starting point to enable us to design a sequence of experiments involving wings with a variety of physical properties.

In addition to validating the quasi-steady model, the first tests allowed us to prove the merits of our experimental methods and the key components. For example, the custom multi-axis force sensor proved adequate, with a sensitivity-bandwidth product that is superior to commercial force sensors and tuned for this load. Also, we have investigated flow visualization techniques for insect-scale flapping wings. This led to the first demonstrations of the feasibility of PIV for insect-scale devices. Through this work, we are the first to demonstrate the use of more traditional flow visualization methods for 1.5 centimeter flapping wings operating at 100Hz and moving with two rotational degrees of freedom.

Using this system, we moved on to study geometric properties of the wings with two goals: to further assess the merits of the experimental infrastructure that we have developed and to explore a part of the design space for flapping-wing MAVs. To make such a study tractable, we vary two parameters: the aspect ratio, *AR*, and the center of area of the wing, $\hat{r}_1$:

$$\hat{r}_1 \equiv \int_0^1 c(\hat{r})\hat{r}d\hat{r}$$

Here, *c* is the normalized radius of the chord a position $\hat{r}$ along the length of the wing (normalized to the wing length). A small $\hat{r}_1$ means that the area of the wing is concentrated proximally while a large $\hat{r}_1$ means that the area is concentrated outboard. These two parameters describe, in a non-dimensional manner, a large space of biologically-relevant wings. We constructed wings to span a portion of aspect ratio and center of area as shown in Fig. 8.

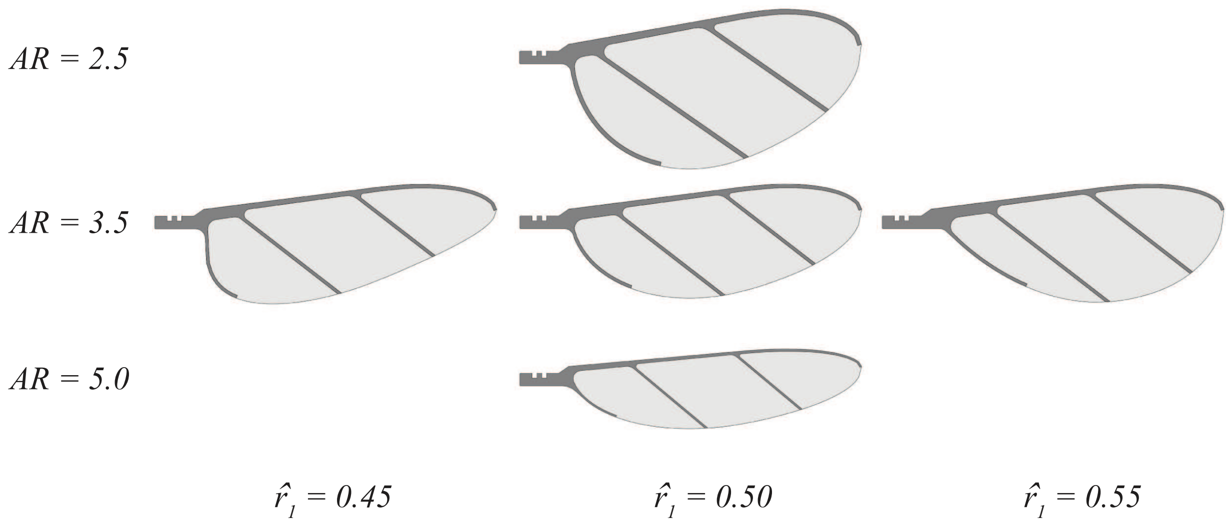

Fig. 8: Wing geometries tested spanning three aspect ratios and three area distributions.

For these experiments, we defined two metrics: the lift coefficient, $\bar{C}_L$, and a power factor defined as:

$$\bar{C}_L^{3/2}/\bar{C}_P\sqrt{AR}$$

where $\bar{C}_P$ is defined as:

$$\bar{C}_P = \frac{AR}{4\rho\Phi^3 f^3 R^5}$$

where Φ is the wing stroke amplitude, f is the wingbeat frequency, and R is the wing length. In this sense, $\bar{C}_P$ describes the mean power consumption and thus the metric $\bar{C}_L^{3/2}/\bar{C}_P\sqrt{AR}$ gives a notion of the lift/power - a key metric for the design of an autonomous vehicle.

We measured the wing flapping motion (and thus stroke amplitude and frequency) and lift force for each wing. This was done for increasing input amplitude of the piezoelectric actuator, and thus increasing stroke amplitude. The results shown in Fig. 9 indicate that a low aspect ratio (large area) wing flapped at as low a total flapping angle Φ as possible is optimal. However, both of these conditions, in the extreme, will likely lead to unfavorable aerodynamics and thus a drop in $\bar{C}_L$ and a rise in $\bar{C}_P$. These experiments are described in more detail in [5].

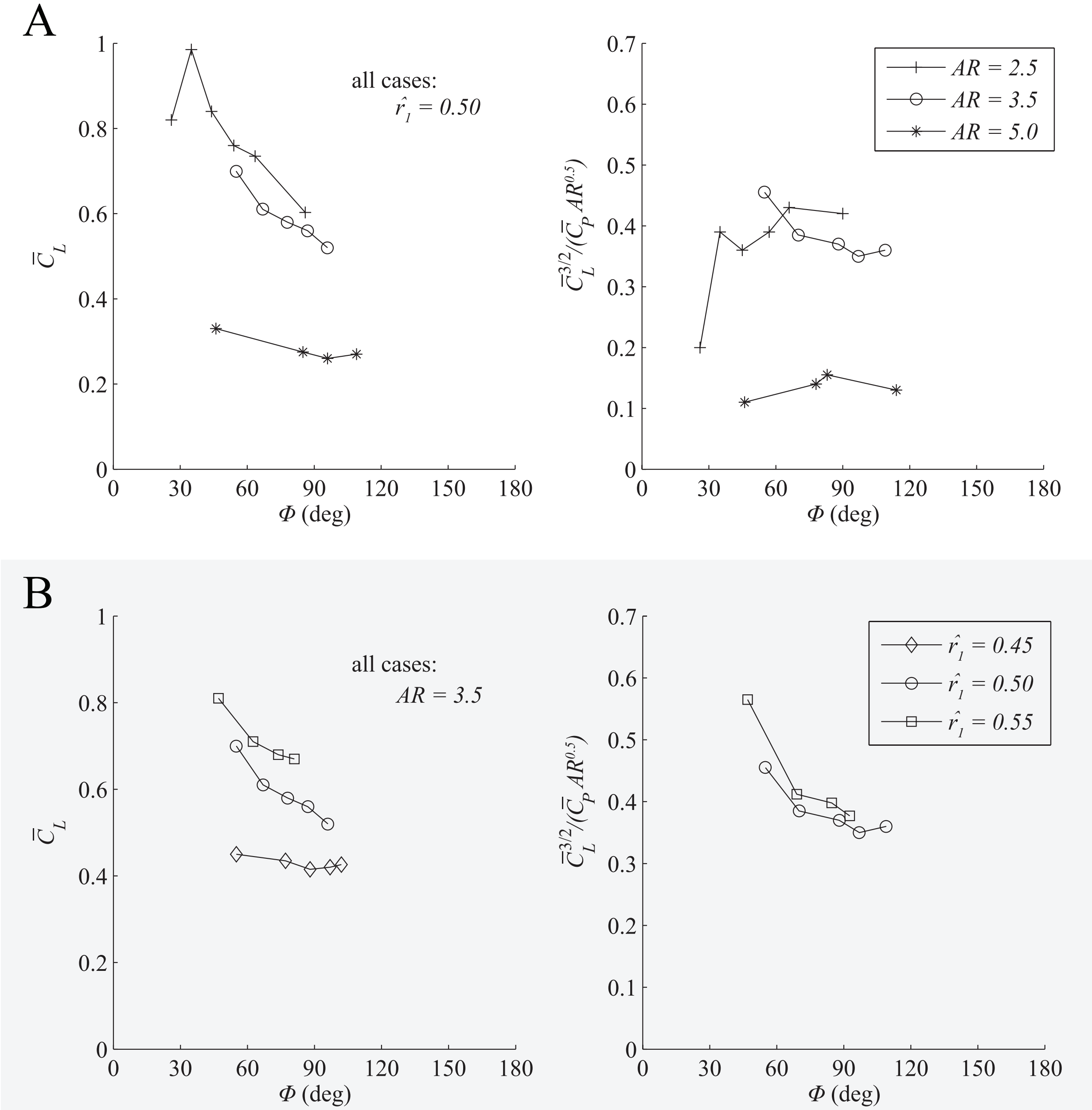

Fig. 9: Results of a study on aspect ratio and area distribution. In A *the area distribution is fixed and in* B *the aspect ratio is fixed.*

These experiments were successful in that (a) we further demonstrated that experimental studies on insect-scale wings is feasible and (b) these experiments provide valuable insights into design features for MAV airfoils.

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1. Whitney and Wood, “Aeromechanics of passive rotation in flapping flight,” *J. Fluid Mechanics*, 660, pp. 197-220, 2010.
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